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Title: X-ray detector development at 100 MHz framerate or above

Author(s): Wang, Zhehui

Intended for: Discussion at DESY on LANL-HIBEF collaboration

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X-ray detector development

At 100 MHz framerate or above

Zhehui (Jeph) Wang

Los Alamos National Laboratory, Los Alamos, NM 87545

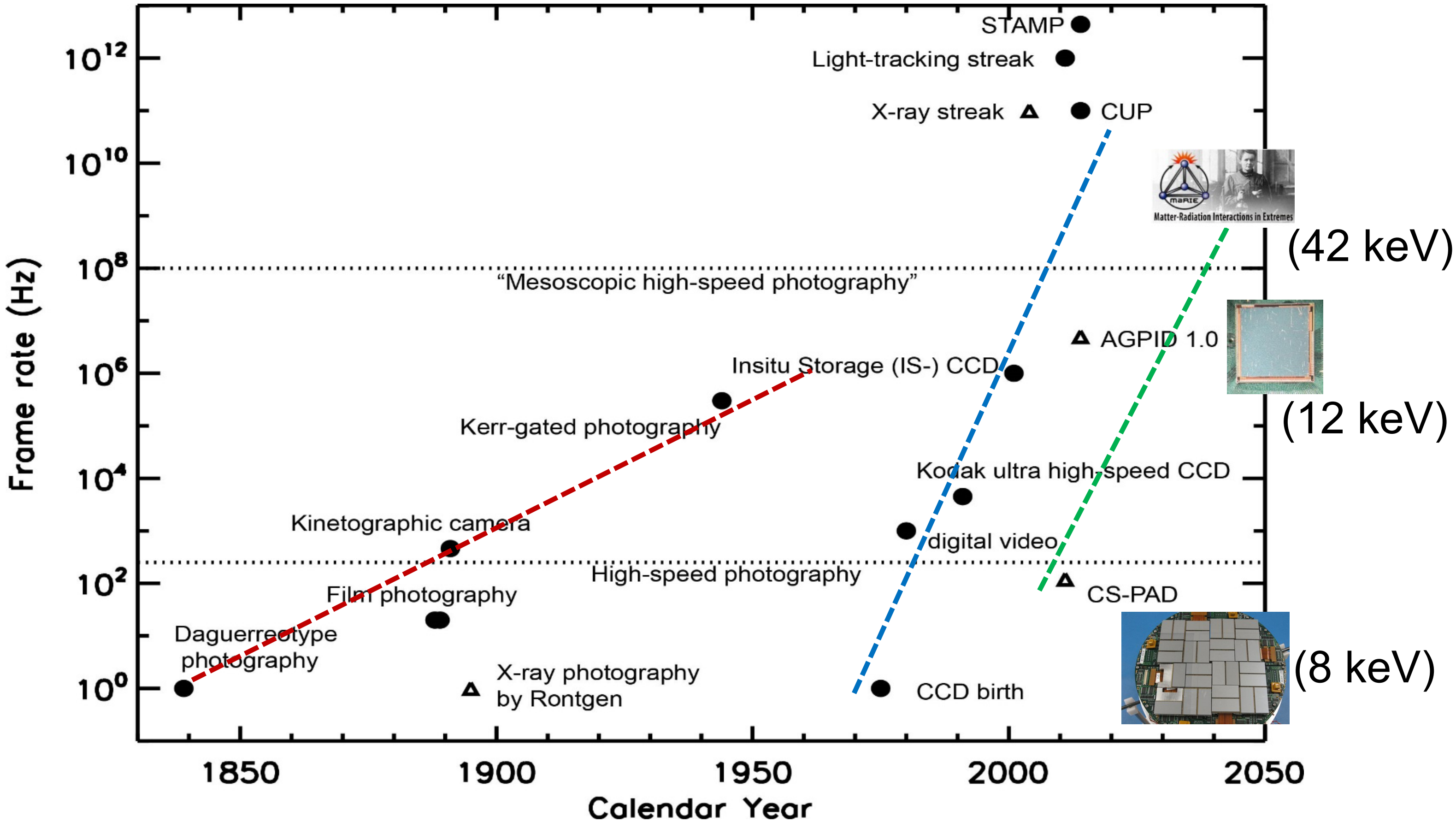
April 8-9, 2019

Eu-XFEL/DESY, Hamburg, DE

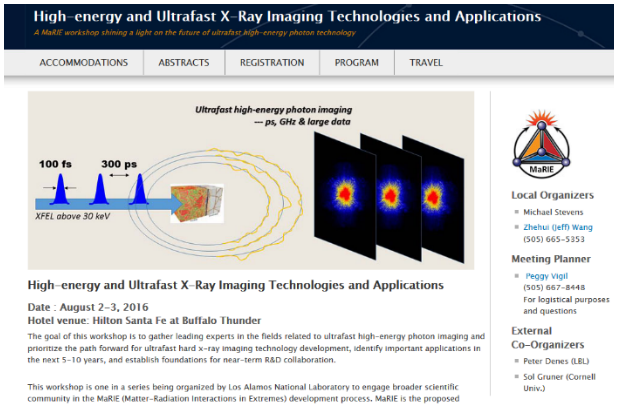
Outline

- **Introduction to the challenges**
  - MaRIE workshops and community wisdoms
  - The state-of-the-art
  - Opportunities
- **Our approach & progress (enabled by collaborations)**
  - New Materials
    - Materials Discovery
  - New Architectures
    - Pushing silicon architecture to higher speeds
  - New data & imaging methods
  - Near term applications Laboratory and APS Experimental tests of materials and imaging
- **Upcoming activities**
  - Development and experimental validation where vision and support coincide
  - ULITIMA 2020 (jointly with ICHSIP33 ~ San Diego, CA, USA)

Evolution of high-speed imaging technologies



The August 2016 workshop surveyed current status And identified future opportunities


High–energy and Ultrafast X–Ray Imaging Technologies and Applications

A MaRIE workshop shining a light on the future of ultrafast high–energy photon technology

ACCOMMODATIONS | ABSTRACTS | REGISTRATION | PROGRAM | TRAVEL

High–energy and Ultrafast X–Ray Imaging Technologies and Applications

Date : August 2–3, 2016
Hotel venue: Hilton Santa Fe at Buffalo Thunder

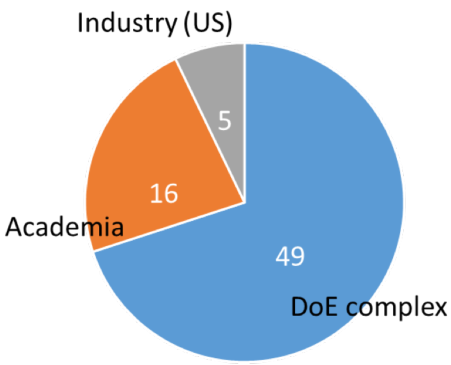
The goal of this workshop is to gather leading experts in the fields related to ultrafast high–energy photon imaging and prioritize the path forward for ultrafast hard x–ray imaging technology development, identify important applications in the next 5–10 years, and establish foundations for near–term R&D collaboration.

This workshop is one in a series being organized by Los Alamos National Laboratory to engage broader scientific community in the MaRIE (Matter–Radiation Interactions in Extremes) development process. MaRIE is the proposed

Local Organizers
- Michael Stevens
- Zhehui (Jeff) Wang
  (505) 665–5353

Meeting Planner
- Peggy Vigil
  (505) 667–8448
  For logistical purposes and questions

External Co–Organizers
- Peter Denes (LBL)
- Sol Gruner (Cornell Univ.)



Ultrafast and High-Energy X-Ray Imaging Technologies & Applications

(August 2-3, 2016; Santa Fe, NM 87506, USA)

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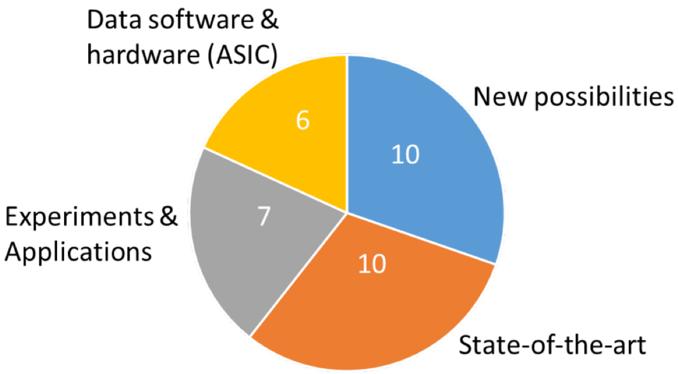


Two-pronged development process: (Low & High Risk)

Performance	Type I imager	Type II imager
X-ray energy	30 keV	42-126 keV
Frame-rate/inter-frame time	0.5 GHz/2 ns	3 GHz / 300 ps
Number of frames	10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	≤ 300 mm	< 300 mm
Dynamic range	10^3 X-ray photons	≥ 10^4 X-ray photons
Pixel format	64 x 64 (scalable to 1 Mpix)	1 Mpix

MaRIE KPP requirements

ASIC/Data	No. Chan.	Analog bandwidth (GHz)	digital sampling (GHz)	S/N (dB)	Bit Res.	CMOS technol.
PSEC4	6	1.5	15		10.5	IBM 130 nm
"Hawaii chip"	128?	3	20	58 dB/ 1Vpp	9.4	(TSMC 130 nm)
"Cornell Keck GHz"	384 x 256	0.5				
epixΔ	1M	3			>= 8	TSMC 250 nm

Analysis of current performance gaps to requirements points to speed and high-energy efficiency as critical issues

	(>50%) x (>20 keV)	Sensor Speed (<10 ns)	ASIC (>0.1 GHz)	No. of Frames (>10)	Resolution (<250 μm)	Dynamic Range (> 10^3)
UXI	< 100 μm Si	-	~ 0.5 GHz	4	25 μm	-
pRad2	< 100 μm Si	50 ns	4 MHz	10	40 μm	<10^3
AGIPD 1.0	500 μm Si	> 10 ns	4.5 MHz	352	200 μm	10^4
KeckPAD	500 μm Si	> 10 ns	6.5 MHz	8	150 μm	> 10^3
ePix100a	500 μm Si	> 10ns	120 Hz	1	25 μm	>10^3
EIGER	450 μm Si	> 10 ns	9 kHz	1	75 μm	> 10^3
Ultra UBSi	< 100 μm Si	-	1 GHz	25	7.4 μm	<10^3
Teledyne Dalsa	< 100 μm Si	-	100 MHz	16	< 50 μm	-

(Credit: C. W. Barnes)

Our vision

* Involve materials scientists to develop new photon conversion materials

"GHz technology"

* Explore new architectures, work with a national collaboration

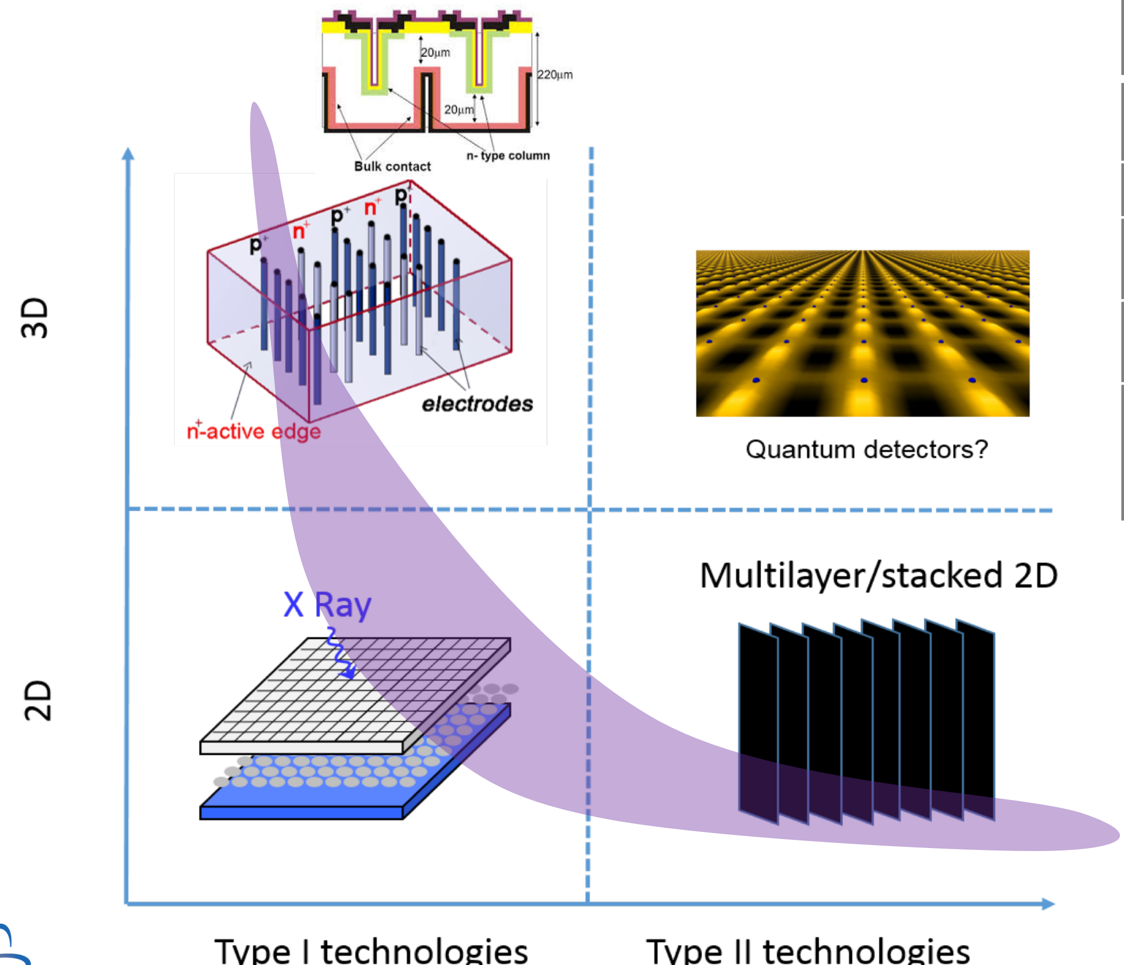
"100 MHz + technology"

* Data-method boosted hardware development & performance

"10 MHz technology"

We are here

1) There are Structural & Processing Innovations that could be pursued



Material Processes	Features
Thin film process	novel thin-film properties
Additive process	Micro-, nano-grains
Microfluidic process	Versatile nano-particle assembly
Polymer-assisted fabrication	Versatile nano-particle assembly
Self-assembly/biological assisted processes	Autonomous

Existing processes:
CMOS,
SOI,
SiGe.

MULTI-LAB (NNSA and DOE/SC) TEAM on advancing silicon

- **ANL**
  - SYNCHROTRON SOURCE (APS)
  - MONOLITHIC DETECTOR TECHNOLOGY (MAPS); MCP & photodetectors benchmark
- **LANL**
  - SYSTEM INTEGRATION, NOVEL STRUCTURES
  - TESTING & APPLICATIONS (IMAGING METHODS, DATA Handling)
- **LBL**
  - ULTRFAST PHOTODETECTORS
- **SNL**
  - CHIPs/ROICs, DESIGNs
- **SLAC**
  - LCLS & OTHER FACILITIES
  - ASIC DESIGNs, HYBRID CONCEPTS

~$20M TPC over 5 years to deliver 100 MHz framing camera for use at DCS@APS or LCLS

UNCLASSIFIED

UMA collaboration

Argonne NATIONAL LABORATORY

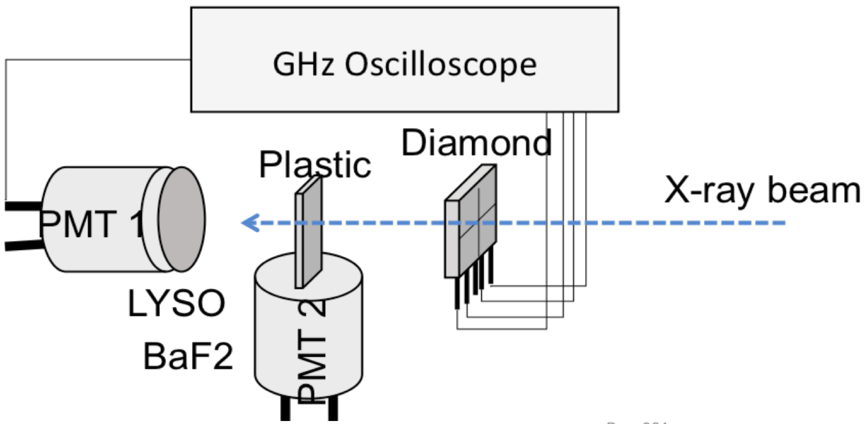
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

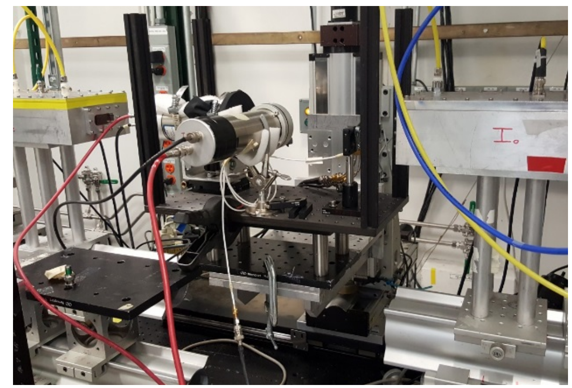
PURDUE UNIVERSITY

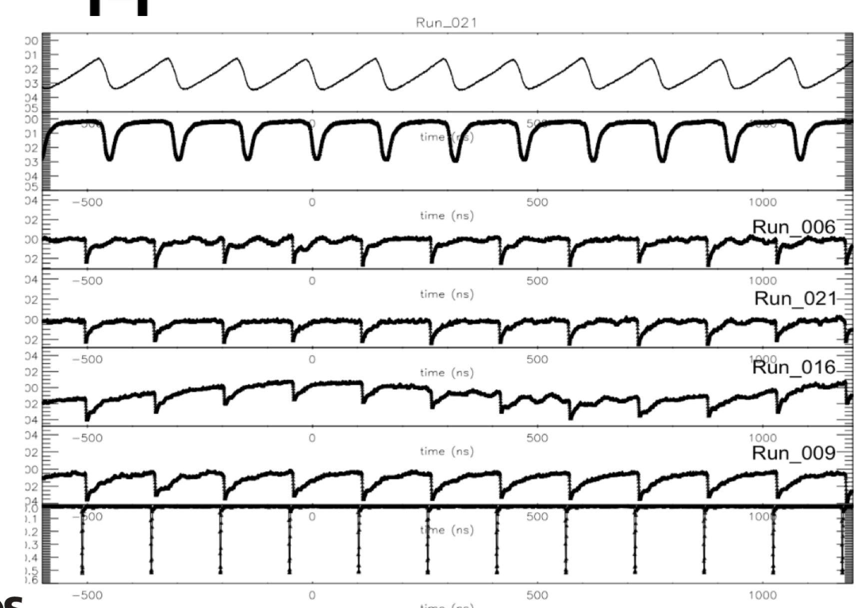
UNIVERSITY OF MARYLAND BALTIMORE COUNTY UMBC 1966

UNIVERSITY OF WISCONSIN

APS Experiment (Feb. 2018)







LYSO + PMT 1

Fast plastic + PMT 2

Diamond (Quadrant A)

Diamond (Quadrant B)

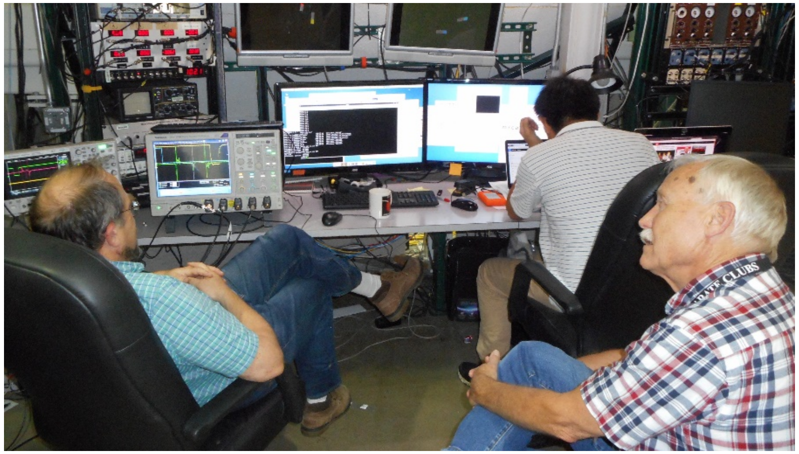
Diamond (Quadrant C)

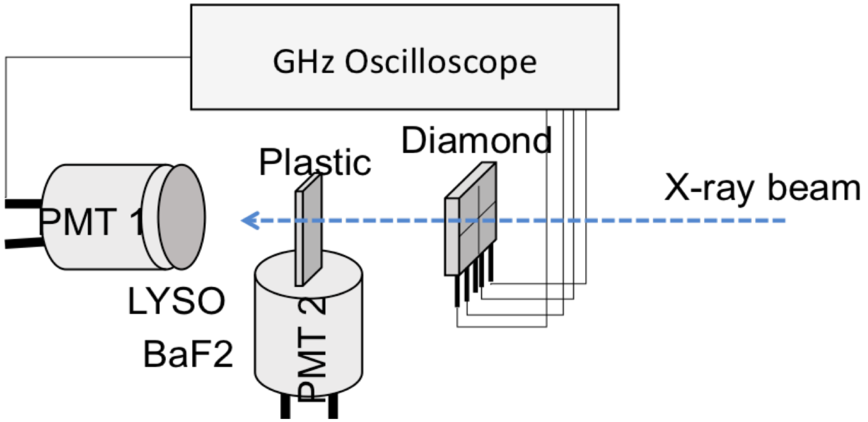
Diamond (Quadrant D)

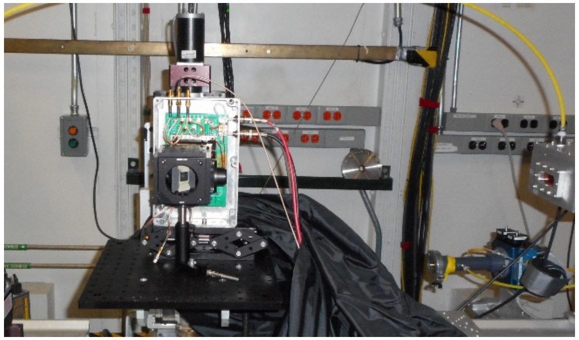
APS timing pulses

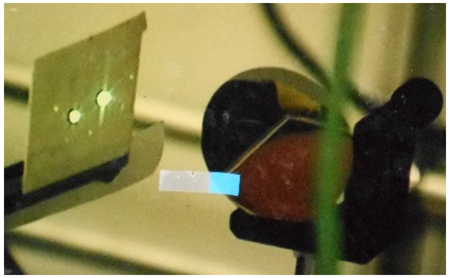
J. Xie et al, NIMA (2019)

APS Experiment (Jul. 2018)





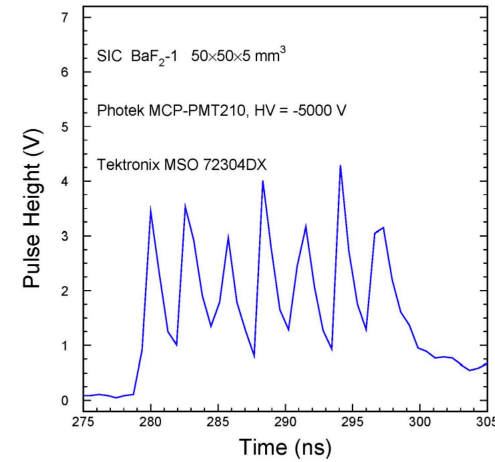




12 fast Scintillators tested

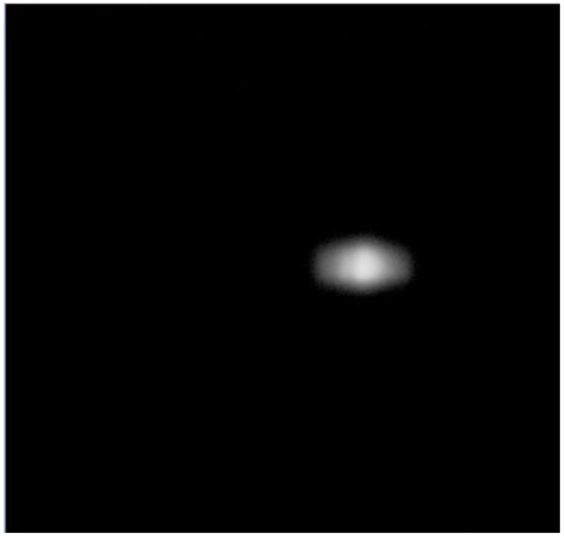
Detector	LYSO+PMT1	Plastic+PMT2	Diamond
Amplitude	20.9 ± 0.4 mV	25.8 ± 0.4 mV	1.9 ± 0.2 mV
Rise time	18.4 ± 0.6 ns	12.4 ± 0.2 ns	2.0 ± 0.2 ns
Decay time	80.7 ± 1.8 ns	26.7 ± 0.9 ns	28.3± 6.2 ns

	BaF_2	BaF_2 (:Y)										
Density (g/cm^3)	4.89	4.89										
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.6	600 0.6	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

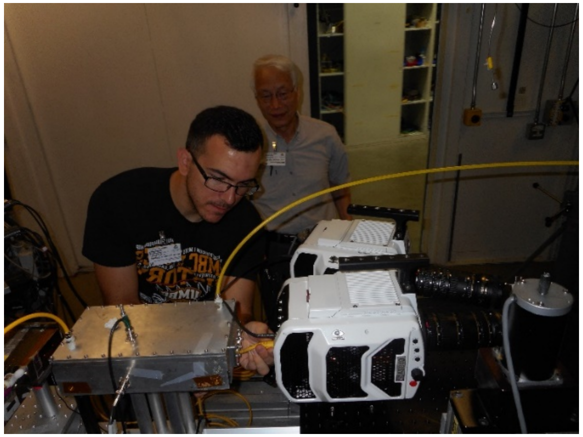


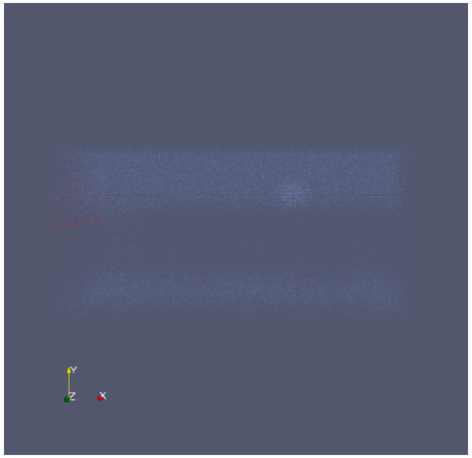
Hybrid mode
2.83 ns bunch spacing

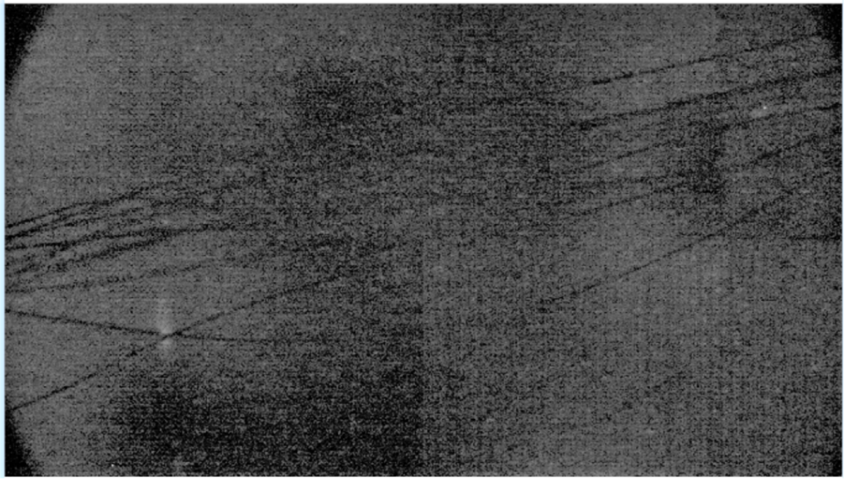
High-energy X-ray Ghost imaging (*preliminary*)



Primary beam

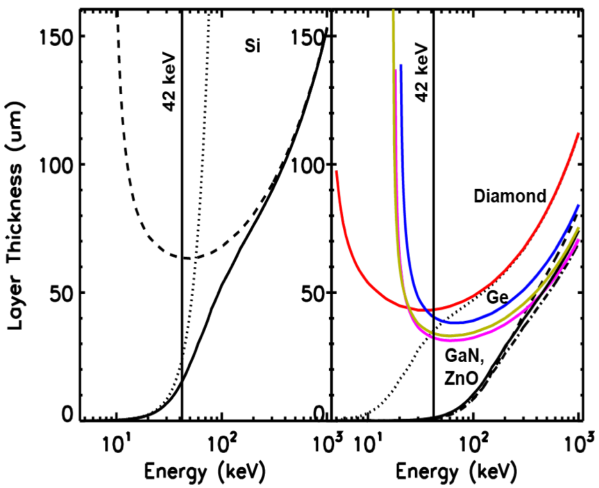




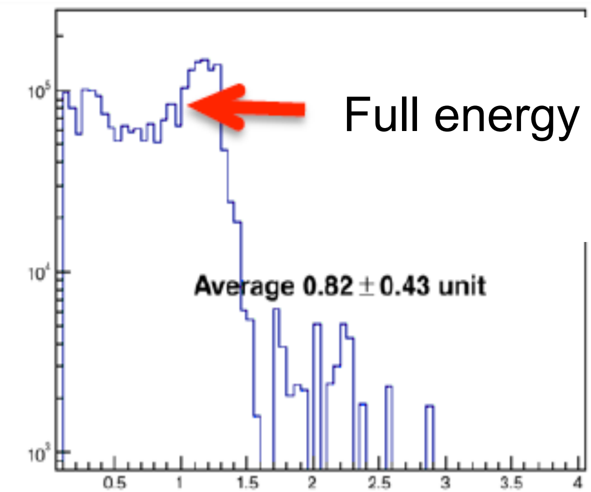


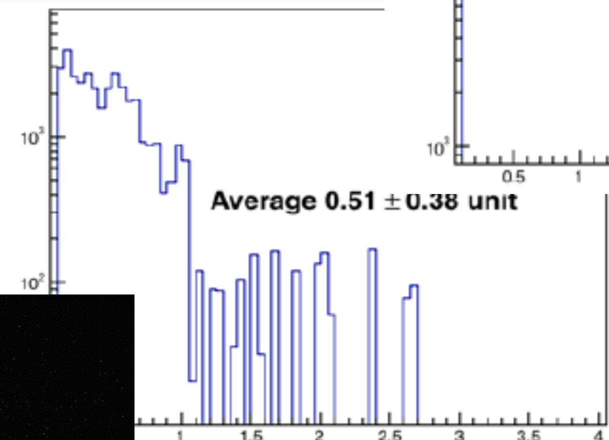
(< 20 um possible)

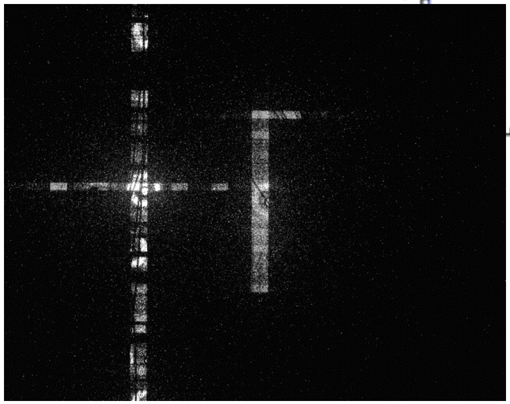
Silicon camera characterization

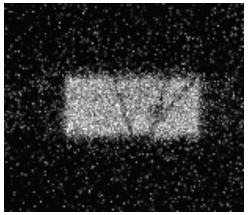


Wang *JINST* 10 (2015) C12013



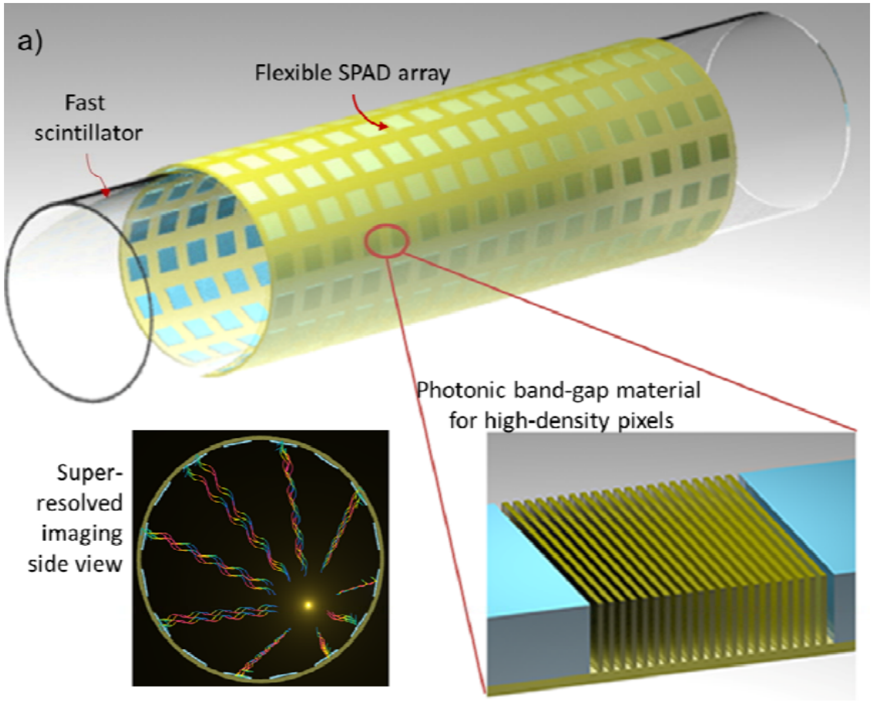


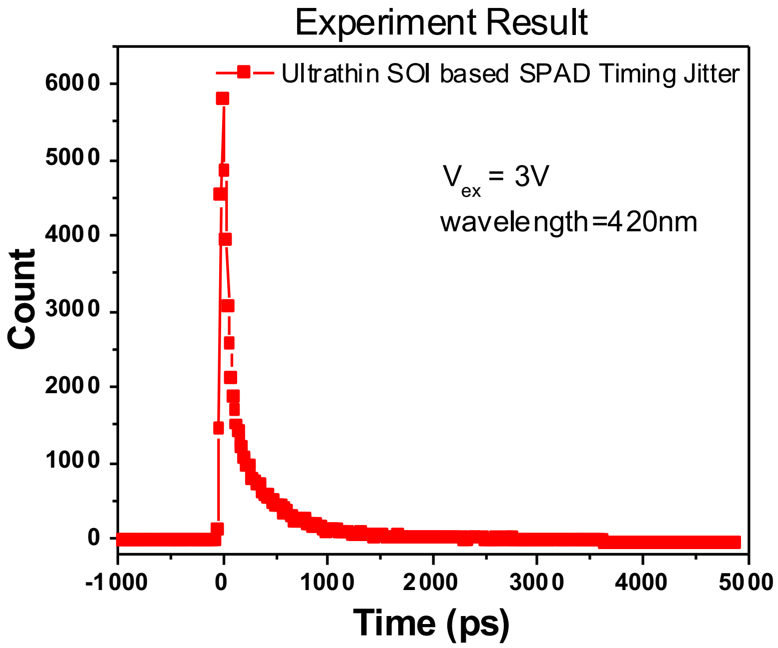




(<10 um resolution)

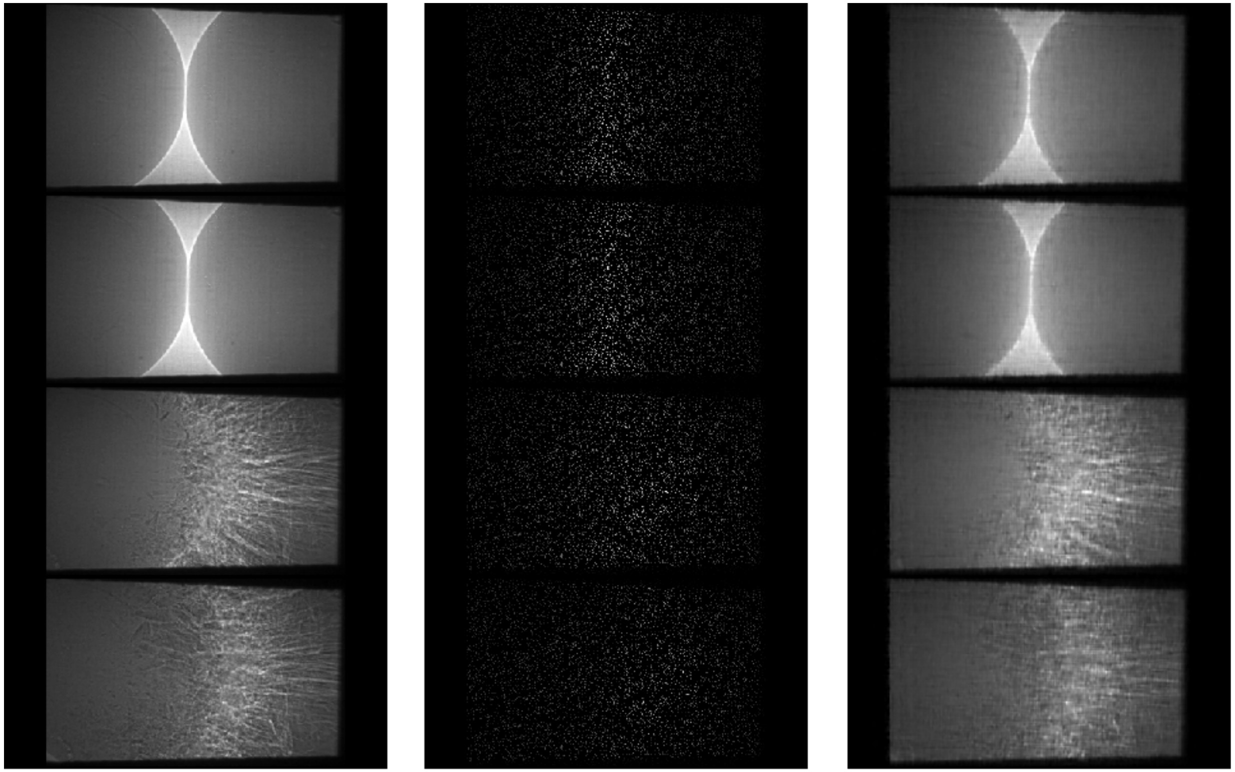
SSAP collaboration –Univ. Wisconsin Madison





3) New data methods like Sparse X-ray imaging can make good images with fewer photons

Wang et al, *JINST* 13 (2018) C01035



(a) (b) (c)

UMA → UDA collaboration

California Institute of Technology 1891

Brookhaven National Laboratory

Argonne National Laboratory

University of California Santa Cruz

Purdue University

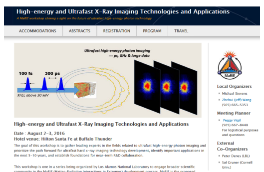
University of Maryland Baltimore County UMBC 1966

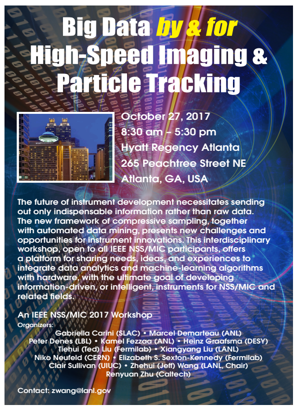
University of Wisconsin

Berkeley University of California

Sandia National Laboratories

We continue to interact, learn from, and collaborate with the best detector teams in the world





ULITIMA2020
+ ICHSIP33

Acknowledgement

J. Bohon

O. Iaroshenko

X. Li

Y. Sechrest

Summary

- **Ultrafast imaging technology development requires inter-disciplinary approach**
- **Data methods can potentially accelerate the development of ultrafast high-energy X-ray imaging technology**
  - For data & by Data
- **A multi-institution & multi-disciplinary team in place**
  - New collaborations in hardware & applications welcome!